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Bone Conduction Systems for Full-Face Respirators: Speech Intelligibility Analysis

by Kimberly A. Pollard, Lamar Garrett, and Phuong Tran

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14. ABSTRACT

Difficult environments, such as Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) environments, pose a unique communication challenge. Effective communication is essential to stay safe in these environments, yet safety gear itself impedes communication. Personal protective equipment (PPE) (e.g., full-face respirators) and noisy decontamination devices (power sprayers, etc.) can impede successful speech transmission. Bone conduction communication systems are a promising solution. These systems are relatively insensitive to background noise and can capture speech directly from a user's skull vibrations, before airborne speech is disrupted by a respirator. To assess the potential of bone conduction systems for use by encapsulated personnel, three communication systems were tested for speech intelligibility using the Modified Rhyme Test (MRT). Sixteen participants wore the M50 Joint Service General Purpose Mask (JSGPM) full-face respirator and communicated via radio using three different communication systems in two levels of background noise. A bone conduction earpiece performed best, followed by a mask-mounted bone conduction system. Both bone conduction systems outperformed the currently-fielded air conduction communication system. The results support the use of bone conduction technology for improved encapsulated communication, which may improve safety and effectiveness for CBRNE personnel. Results are discussed and recommendations are provided.

15. SUBJECT TERMS

bone conduction, speech intelligibility, protective mask

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1. Introduction

Communication (from Latin "*communis*," meaning *to share*) is the exchange of thoughts, messages, and information by speech, writing, behavior, or signals (Webster, 2002). Communication while encapsulated (i.e., while wearing extensive safety gear such as full-face respirators) has long been recognized as a significant challenge. Communication in a dangerous environment, such as a military or civilian Chemical, Biological, Radiological, Nuclear, or Explosive (CBRNE) environment, must be unambiguous and comprehensible to avoid possible fatal accidents and misunderstanding. However, encapsulation gear (full-face respirators, etc.) introduce significant barriers to speech intelligibility. We first observed issues with encapsulated communication during the United Kingdom exercise “Liquid Chase” back in the early 1980s and during the Combined Arms in a Nuclear/Chemical Environment (CANE) and Force Development Test and Experimentation (FDTE) exercises (1983–1993). In spite of the CBRNE community’s efforts, the issue remains a challenge.

A recent (2012) operational demonstration of the Hazard Mitigation, Materiel and Equipment Restoration (HaMMER) Family of Systems (FoS) further illustrated this issue. The CBRNE Soldiers and Marines participating in the HaMMER demonstration encountered severe speech intelligibility difficulty which restricted their ability to adequately communicate with each other, even at short line-of-sight distances (10 meters), during the decontamination training missions. The most prevalent issues identified during the exercise were difficulties understanding speech, overlapping speech, missing acknowledgments, mumbled or garbled speech sound, and high audible background noise during decontamination operations. This resulted in longer mission duration, increased heat stress, and mission degradation. Therefore, despite the many advances in communications technology, enabling communication in a CBRNE operational environment was identified by the Office of the United States Assistant Secretary of the Army for Acquisition, Logistics, and Technology[*] as one of the Army Top 10 Challenges in Fiscal Year 2013.

Bone conduction systems are a promising solution to the communication difficulties posed by high noise levels in decontamination environments (from power sprayers, vehicle engines, and other equipment). Bone conduction is also a promising solution to communication difficulties posed by the disruptive effect that a respirator has on airborne speech. Bone conduction communication technology can transmit speech signals to and from the user through contact transducers placed anywhere on the user’s head, which leaves the ear canals open or covered (protected) as needed without affecting the communication interface (Henry and Letowski, 2007). Bone conduction microphones are largely insensitive to background noise, due to the impedance mismatch between air and solid media like bone. Furthermore, since bone conduction

[*]ASA(ALT).

microphones allow speech to be captured before it travels through the respirator, any airborne garbling or muffling induced by the respirator itself can be avoided. It is thus likely that bone conduction systems can improve speech intelligibility levels for encapsulated personnel, compared to the levels achieved using the current fielded technology, which is based on air conduction.

This study used the Modified Rhyme Test (MRT) to measure speech intelligibility. The MRT is one of three American National Standards Institute (ANSI) standardized word tests for measuring the intelligibility of speech over communication systems, and has been demonstrated to be highly correlated with results obtained with vocabularies representative of operational military communications (ANSI/ASA S3.2-2009). The MRT was selected for its ease of automation, the low probability of correct guessing, and because it allowed assessment of intelligibility at both the beginnings and ends of words.

2. Objective

The goal of the present study was to assess the feasibility of using removable bone conduction communication devices for radio communication while encapsulated, specifically, while wearing the M50 Joint Service General Purpose Mask (JSGPM) full-face respirator. This study was conducted to determine the feasibility of using bone conduction technology to replace (entirely or partly) the currently fielded system, the JSGPM Voice Projection Unit (VPU). The goal of the present study was to evaluate the effectiveness of the VPU and two alternative bone conduction systems by measuring speech intelligibility for encapsulated participants using these systems.

3. Methodology

3.1 Equipment

The present study examined the speech intelligibility of three communications systems when used with the M50 JSGPM chemical-biological protective mask, a full-face respirator. One air conduction system and two bone conduction systems were explored. The first system, the JSGPM VPU, is the current fielded communication system for encapsulated CBRNE Warfighters. This device uses an air conduction microphone fitted on the inside of the mask mouthpiece, which connects to a small air conduction loudspeaker fitted on the outside of the mask mouthpiece (figure 1). The second system, the Huari HRE-5673, is a 2-piece bone conduction system designed to be mounted on the straps of a respirator. The U.S. Army Research Laboratory (ARL) modified the mounting system so that it fit with the M50 JSGPM. This was done by trimming excess rubber from the mask-attachment pieces, which, off the shelf, were too large for the M50 JSGPM. The bone microphone piece of the HRE-5673 is

held against the center of the forehead using an ARL-made elastic band threaded around the mask straps (see figure 2). The bone vibrator piece of the HRE-5673 is held against the cheek region (mandibular condyle and/or zygomatic arch) using a rubberized band threaded onto the mask straps (see figures 2 and 3 for current ARL-modified design). ARL also applied a thin layer of polymer coating to the skin-contact area of the bone vibrator piece to enhance comfort for the user. The third system, the Temco EM20N-T, is an all-in-one bone microphone-bone vibrator system designed to be worn in the ear (figure 4). The earpiece does not interfere with the respirator and does not require attachment to the respirator.

Figure 1. VPU attached to the M50 JSGPM. Multiband Inter/Intra Team Radio (MBITR) is also shown.

Figure 2. Modified HRE-5673 attached to the M50 JSGPM. The VPU is not worn at the same time as the HRE-5673 or the EM20N-T and is not shown here.

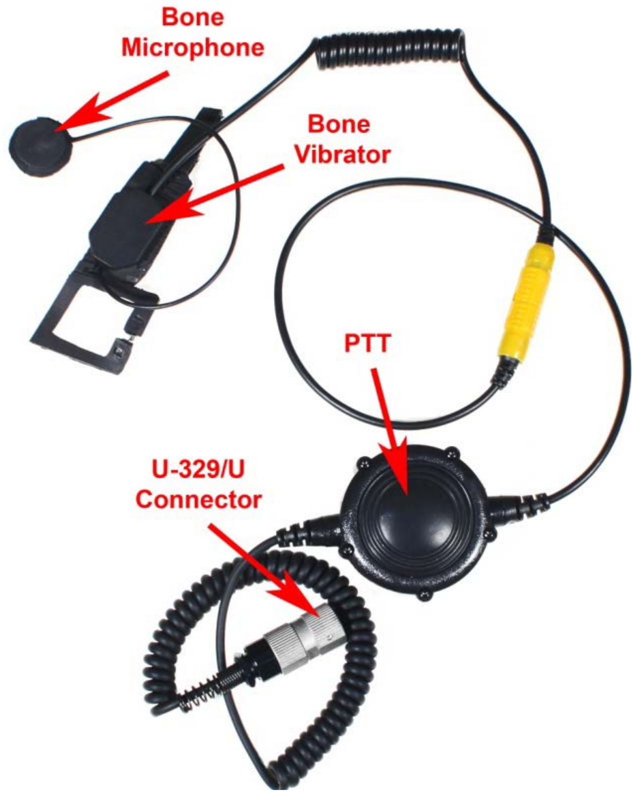

Figure 3. Modified HRE-5673 with push-to-talk (PTT).

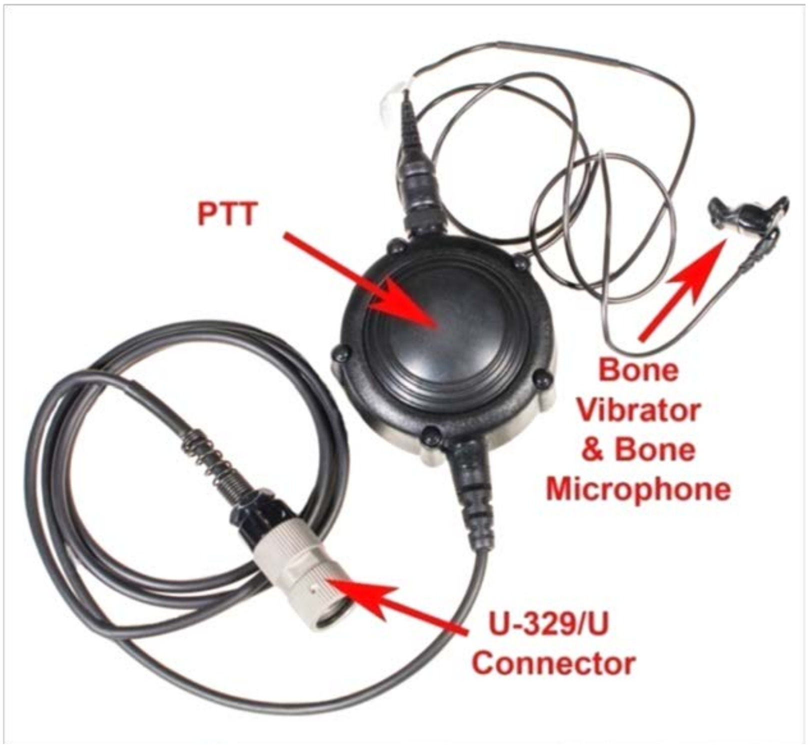

Figure 4. EM20N-T with PTT.

Thales Multiband Inter/Intra Team Radio (MBITR) AN/PRC 148 tactical radios were used, with PTT systems, to send and receive the communication signals. The PTT systems used varied by communications device. For the VPU trials, participants used the radios' built-in PTT, internal loudspeaker, and microphone, as is typically done in the field. For the HRE-5673 trials, HRE-5673 PTT systems were used. These had to be modified with U-329/U connectors to make them compatible with MBITR radios. The Temco EM20N-T trials used Temco PTT systems.

Because some background conditions involved potentially hazardous levels of noise, and because real-world CBRNE activities often occur in similar levels of noise, participants wore hearing protection devices (HPDs) during all trials. While using the VPU or HRE-5673, participants wore Combat Arms Earplugs (CAE) (figure 5), turned to the steady-state noise setting. Since the EM20N-T system is worn in the ear, it precluded concurrent use of the CAE. For trials using the EM20N-T, participants wore over-the-ear HPDs (E.A.R Ear-muff, model 3000) (figure 6). In addition to the M50 JSGPM mask, participants wore Joint Service Lightweight Integrated Suit Technology (JSLIST) protective jackets with hoods and Air Warrior Survival Vest Carrier cargo vests. Hoods were worn up in all conditions except the EM20N-T, because the over-the-ear HPDs could not be worn on top of the hoods.

Figure 5. Combat arms earplugs.

Figure 6. E.A.R. Ear-muff model 3000.

Background noise (M113 vehicle noise) was played through Electro-Voice Sx500+ loudspeakers arranged outdoors in the Open EAR portion of ARL's Environment for Auditory Research (EAR) facility. Background noise was played at 66 decibels, A-weighted (dBA) and at 90 dBA, as measured at the location of the participant's ear (with participant present) using a B&K type 2225 sound level meter, slow response. The 90 dBA level was chosen to re-create noise conditions CBRNE personnel can expect in an operational environment. Military and commercial vehicles, decontamination equipment (power washers, etc.), and generators all produce high levels of noise. The 66 dBA level represents an ideal outdoor condition with minimal vehicle and machine noise.

3.2 Participants

Sixteen participants (11 male, 5 female) between the ages of 18 and 40 were recruited from the civilian population located near Aberdeen Proving Ground, Maryland. Hearing screenings were performed on all participants. Fifteen participants had pure tone hearing thresholds below 25 dB hearing level (HL) in both ears at all test frequencies (125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz). One male participant had mild hearing loss in the right ear at 4000 Hz, with a pure tone threshold below 30 dB HL. All participants were native speakers of American English, and none had any signs of or reported any history of otologic problems. The participant with hearing loss was used as a talker but not as a listener for MRT trials. All other participants were used as both talkers and listeners.

After signing the volunteer agreement affidavit (VAA) (see appendix A), each participant was measured and subsequently fitted with an appropriately-sized M50 JSGPM chemical-biological protective mask (full-face respirator). Participants then donned a JSLIST protective jacket and an Air Warrior Survival Vest Carrier cargo vest and were handed a Thales MBITR radio (see figures 7 and 8). The radio volume levels were set at one notch below maximum for all trials, unless a participant reported that this was uncomfortably loud, in which case the volume level was set to two notches below maximum for that participant. Each participant was also fitted with each of the three communications systems, one at a time, as appropriate for the specific trial.

Trials took place in the outdoor Open EAR facility at Aberdeen Proving Ground. Each participant was seated in a folding chair, approximately one meter from an Electro-Voice Sx500+ loudspeaker and 65–75 m from their communication partner (sitting in front of a different EV Sx500+ loudspeaker) (figure 9). Portable canopy tents were used to provide shade. Participants were given breaks between communication device models or as requested, and were provided with bottled water and sports drinks.

Figure 7. Front view of participant configuration.

Figure 8. Side view of participant configuration.

Figure 9. Two talker-listener teams are shown participating in the study in ARL's Open EAR outdoor facility. Shade tents were not used on this particular day due to chilly weather. EV Ex500+ loudspeakers sit against the grey control stations, approximately one meter in front of each participant, and play background noise.

3.3 Study Design

The speech intelligibility test used in this study was the MRT. The MRT is a standardized word test recommended by ANSI for measuring the intelligibility of speech over communication systems (ANSI/ASA S3.2-2009). MRT scores have been demonstrated to be highly correlated with results obtained with vocabularies representative of operational military communications (ANSI/ASA S3.2-2009).

The MRT consists of 300 monosyllabic consonant-vowel-consonant (CVC) English words divided into 50 six-word groups. The words in each group sound very similar and differ only by initial or final phoneme (see appendix B). A single administration of the test consists of a list of 50 target items--one word from each group--spoken in a carrier phrase. During a single test trial, a target word is spoken by the talker and the listener selects which of the given six words in the group was the one that was spoken. It is a closed set test with the random probability of a correct guess equal to 1/6 (16.7%).

Participants were instructed on appropriate pronunciation and cadence for use in the MRT and were assigned communication partners with whom they would work for the duration of the study. Participants were then instructed to practice serving as talkers and listeners, both while wearing and not wearing the JSGPM. Training was deemed sufficient once a participant could

consecutively correctly communicate 10 MRT words in indoor quiet. When participants reported they were comfortable with the word lists, procedure, and equipment, trials were begun. During a trial, one partner would serve as the talker while the other would serve as a listener, and then they would switch roles (figures 10 and 11). Each set of partners communicated on a different radio channel/frequency so there would be no signal overlap across sets of partners. Each partner set communicated under two noise conditions (66 dBA and 90 dBA) using three communication systems (VPU, modified HRE-5673, and EM20N-T), for a 2 × 3 design. Within a trial, each partner would serve as a talker for one word list and as a listener for another word list. Talkers were handed pre-printed randomized lists of MRT words to read during the trial (see appendix C for sample). The talker would read each word embedded in the carrier phrase "Mark the ____ again." The listener would then circle the word they heard, using a pre-printed sheet of candidate MRT words (appendix B). After 50 phrases, the talker and listener would switch roles and use a new pre-printed sheet of randomized words.

The presentation order of noise levels and device types was counterbalanced across trials, with the restriction that all trials using a given device type were performed consecutively (to avoid the hassle and discomfort of repeatedly donning and doffing the respirators).

Figure 10. Test participant serving as a talker using the HRE-5673.

Figure 11. Test participant serving as a listener using the HRE-5673.

3.4 Data Analysis

Completed data sheets were scored by hand, and the number of correct responses by each listener in each trial was recorded. The MRT is a multiple-choice test with six possible answers for each question. Therefore, raw scores were adjusted to account for guessing (ANSI/ASA S3.2-2009), according to the formula

$$R_A = R - \frac{W}{n-1} = R - \left(\frac{W}{5}\right) \tag{1}$$

in which R_A is the number of correct responses adjusted for chance, R is the number of correct responses, W is the number of incorrect responses, and n is the number of alternate choices per item (for the MRT, n = 6). To avoid potential ceiling effects, the adjusted data were transformed into rationalized arcsine units (RAUs) before analysis (Studebaker, 1985), using the formulae

$$\theta = \arcsin\sqrt{\mathrm{X}/(\mathrm{N}+1)} + \arcsin\sqrt{(X+1)/(N+1)} \tag{2}$$

$$RAU = \left(\frac{146}{\pi}\right)\theta - 23 \tag{3}$$

where X is the number of correct responses and N is the number of items in the test (50 for our tests). These formulae are appropriate if the number of items in the test is less than 150 (Studebaker, 1985). RAU-transformed adjusted scores served as the dependent variable. Independent variables included communications device, background noise level, and talker gender. Data were subjected to analysis of variance (ANOVA) and t-tests.

4. Results

In both noise conditions, the EM20N-T bone conduction earpiece yielded the highest MRT scores, followed by the modified HRE-5673 bone conduction system (tables 1 and 2, figure 12). Pairwise comparisons revealed that the EM20N-T significantly outperformed the VPU in 90 dBA (t-test, $t_{28} = 3.520$, $p = 0.001$) and in 66 dBA (t-test, $t_{28} = 2.224$, $p = 0.034$). Without controlling for talker traits, differences between the VPU and HRE-5673 did not reach statistical significance at either noise level, nor did differences between the HRE-5673 and the EM20N-T. As expected, MRT scores were lower for the 90 dBA condition as compared to the 66 dBA condition (t-test, $t_{88} = 6.274$, $p < 0.001$). This was true for all communication device models.

Table 1. Mean raw MRT scores (unadjusted, untransformed percentage correct) ± standard deviation for all conditions evaluated in this study.

	66 dB A	**90 dB A**
HRE-5673	74.93 ± 12.19	55.73 ± 16.71
EM20N-T	77.47 ± 8.53	65.33 ± 14.38
VPU	70.80 ± 8.10	46.53 ± 14.63

Table 2. Mean RAU-transformed adjusted MRT scores (percentage correct) ± standard deviation for all conditions evaluated in this study.

	66 dB A	**90 dB A**
HRE-5673	69.56 ± 14.87	46.92 ± 19.42
EM20N-T	72.18 ± 10.30	58.06 ± 16.53
VPU	64.14 ± 9.49	35.92 ± 17.89

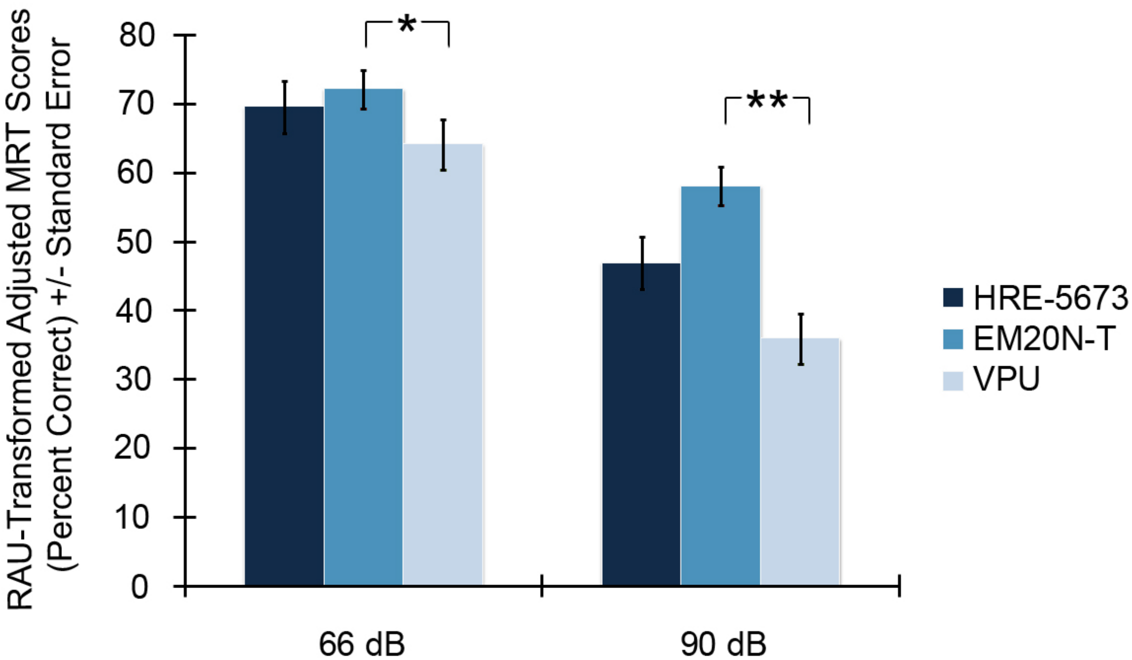

Figure 12. RAU-transformed adjusted MRT scores (percentage correct) for each communications device in each background noise condition. A single asterisk indicates significant difference at α<0.05, double asterisk at α<0.01, before controlling for talker gender.

An ANOVA was performed using RAU-transformed adjusted percentage correct as the response variable, noise level and communications device as fixed factors, and the talker's gender as a random factor. All three factors influenced speech intelligibility as main effects (table 3). As expected, MRT scores were higher in the quieter noise condition. The Temco EM20N-T earpiece device yielded the highest MRT scores, followed by the HRE-5673. The VPU yielded the lowest scores. Additionally, higher MRT scores were achieved when male participants were talking vs. when female participants were talking. All differences were statistically significant at the α<0.05 level. As before, the EM20N-T significantly outperformed the VPU. Notably, after controlling for both noise level and talker gender, the HRE-5673 also significantly outperformed the VPU.

Table 3. ANOVA results for MRT speech intelligibility.

	F	***P* value**	**partial η^2**
noise	48.940	<0.001	0.365
talker's gender	8.550	0.004	0.091
comm. system	7.937	<0.001	0.157
HRE-5673		0.033	0.052
EM20N-T		<0.001	0.157
VPU		(redundant)	

5. Discussion and Recommendations

The bone conduction systems numerically outperformed the air conduction VPU system in both noise conditions. Higher background noise had a negative effect on speech intelligibility for all systems, with MRT scores substantially lower for the 90 dBA condition as compared to the 66 dBA condition. This is consistent with previous studies (e.g., McBride et al., 2008a, Osafo-Yeboah et al., 2009, Tran and Letowski, 2010). The 90 dBA noise condition is the more realistic representation of noise conditions CBRNE personnel can expect in an operational environment, and is thus the most critical condition to consider. In 90 dBA noise, the average MRT performance (RAU-transformed adjusted percentage correct) was 22.1 percentage points higher for the best bone conduction system than for the air-conduction VPU system (58.1% for the EM20N-T versus 35.9% for the VPU), thus, a 61.6% increase in speech intelligibility over the currently fielded VPU system. This difference is substantial, and indicates a promising avenue to improve communication for encapsulated personnel using bone conduction technology.

The VPU is a fairly effective communication device for encapsulated personnel, especially in quiet conditions, but it does not perform as well under high noise conditions. Use of the VPU with a handheld radio (and the radio's internal microphone and loudspeaker—current standard practice for CBRNE warfighters) was difficult under high noise conditions because background noise, in addition to speech, was picked up by the devices and transmitted to the listener. This is a common issue with air conduction systems, one that a bone conduction system may be better able to circumvent. Because of the impedance mismatch between air and body tissues (e.g., skull bone), bone conduction microphones are relatively insensitive to environmental background noise in the ambient air. As a result, a higher speech signal-to-noise ratio is transmitted to the listener, and thus speech may be easier to understand (Henry and Letowski, 2007). Furthermore, by picking up speech signals directly from skull vibrations, a bone conduction device can bypass any air-related speech-distorting effects of a respirator, further enhancing the bone conduction system's performance. Recent advances in bone conduction technology have revolutionized the field and led to a variety of new communications systems, some of which may be used while wearing full-face respirators. The two bone conduction systems tested in the current study yielded higher MRT scores in both noise conditions, and the difference between the EM20N-T and the VPU, especially in 90 dBA noise, was sizable and strongly statistically significant. This improved performance is likely heavily due to bone conduction's relative insensitivity to background noise.

The EM20N-T yielded higher speech intelligibility scores than the other bone conduction system, the modified HRE-5673, though the differences did not reach statistical significance. Both devices utilize advantageous bone conduction skull locations. The EM20N-T places its bone vibrator in the ear canal, which situates it very close to the cochlea; excellent transmission

can be expected from that location. The HRE-5673 situates its bone vibrator and bone microphone on external skull locations (mandibular condyle and forehead, respectively) that are known to be excellent for speech transmission. The forehead has been found to be the best external skull location for speech clarity from bone microphones (Tran et al., 2008, McBride et al., 2011), and the condyle has been found to be the most sensitive external skull location for receiving bone conducted signals (McBride et al., 2008b). A possible reason for the EM20N-T earpiece's improved performance over the HRE-5673 may be the relative ease of use. The HRE-5673 was a bit awkward to place and did not fit perfectly on all users. For example, some users did not have adequate bare forehead space between their fitted mask and hairline, which meant the microphone had to be partially placed on top of hair, and this may have degraded performance. Similarly, the bone vibrator sat in a slightly different cheek location based on the size and shape of the user's head. In contrast, the earpiece device was simple to insert for all users, and there was no worry about physical interference from hair or from the mask itself. Electronic or other device parameters may also have contributed to the difference. Due to ease of use, the lack of potential interference with the full-face respirator, and the better speech intelligibility performance, we would advocate the EM20N-T or a similar earpiece device over the HRE-5673 or a similar device, provided hearing protection concerns can be accommodated for CBRNE warfighters and other encapsulated personnel (see recommendations below).

One concern is that unavoidable differences in hood use and HPDs during the test may have had an influence on speech intelligibility. The earmuff (worn only with the EM20N-T) precluded the wearing of the JSLIST hood, and the hood may have attenuated environmental sound and/or added fabric noise for the HRE-5673 and VPU conditions. Pilot testing revealed no perceived differences as a function of hood use, so we expect that any such differences were small and could not account for the large speech intelligibility differences seen between systems in this study. The difference in HPD use is of greater concern. The physical shape of the different communications systems necessitated the use of different HPDs: the EM20N-T could not be worn with a CAE, and the HRE-5673 could not be worn with an earmuff. Both the CAE and the earmuff attenuated environmental noise for the talker's ears and listener's ears, but the earmuff also attenuated environmental noise for the talker's EM20N-T bone microphone. While bone microphones are largely insensitive to air-conducted noise, they are not entirely impervious. The earmuff could have therefore given the EM20N-T bone microphone an advantage by exposing it to less air-conducted background noise, which might mean less noise was transmitted via radio to the listener. Pilot tests examined the EM20N-T microphone's sensitivity to air-conducted noise. The earpiece was dangled in sound fields of approximately 66 dBA and 90 dBA M113 vehicle noise, and the signal was transmitted via MBITR radio to a listener wearing another EM20N-T indoors in quiet. The 66 dBA environment did not lead to noticeable background noise being transmitted to the listener. We therefore expect that the earmuff afforded virtually zero advantage to the EM20N-T in the 66 dBA study conditions. In the 90 dBA pilot test, a small amount of background noise was heard by the listener. This suggests that the earmuffs afforded perhaps a small advantage in the 90 dBA study conditions. If the EM20N-T's sole advantage was

an artifact of earmuff use, we would expect no significant difference at 66 dBA and perhaps only a small difference at 90 dBA. However, we found a significant speech intelligibility difference at 66 dBA and a large significant difference at 90 dBA. We therefore expect the EM20N-T itself was responsible for most of the improved performance. Nonetheless, an ideal test would use an EM20N-T earpiece modified to include hearing protection, worn with a CAE in the opposite ear, and worn with the hood up. Since the current EM20N-T does not offer hearing protection, this option was not possible for this study.

In this study, male talkers were better understood than female talkers. This is consistent with previous studies (e.g., McBride et al., 2008a), including an ARL study which found that male talkers tended to be better understood than female talkers when using a bone conduction microphone worn on the forehead (Pollard et al., in review). In the current study, the HRE-5673's microphone was placed on the forehead, so we would predict a small advantage for male talkers. However, this forehead placement does not entirely explain the gender differences observed. The male talker advantage was greater when using the EM20N-T earpiece than when using the HRE-5673 forehead microphone. The reasons for this are unclear, but may have to do with device specifications (e.g., frequency response), or may be due to sizing issues. Nonetheless, the EM20N-T still yielded the best MRT scores for both male and female talkers.

Bone conduction communication devices appear promising for use by CBRNE warfighters and other encapsulated personnel. The improvement in speech intelligibility over the current fielded system was substantial. However, there is still room for improvement. Most importantly, the EM20N-T earpiece needs to be modified to include hearing protection. Hearing protection is necessary in high-noise operational environments, and over-the-ear HPDs are not practical while encapsulated. The addition of flexible flanges to the earpiece, much like the flanges on a CAE, could potentially provide sufficient hearing protection to the user. An even better option would be to do an individual ear mold for each user; this would maximize the earpiece's comfort, stability, and good fit for hearing protection. Either a companion customized HPD, or a CAE, could be worn in the opposite ear. In addition, a plastic or rubberized hook to go around the ear would also be desirable; this would prevent the earpiece from accidentally being dislodged or falling down. The HRE-5673, if pursued as a communication system for encapsulated personnel, also would benefit from several modifications (see figure 2 for current design). The cheek piece should be streamlined to better fit in line with the respirator and to avoid pinching or covering the ear. A curved surface may also provide better contact than the currently flat surface. Flexible and adjustable mountings would make it easier to position the devices on each individual user and could allow alternative placements if necessary. Critically, the forehead piece needs to be attached in such a way that the cord connecting the two pieces is not a snag hazard. A built-in adjustable, flexible forehead band would also be desirable. These modifications would make the devices easier to use, more comfortable to wear, and easier to properly place for best performance. In addition to making and testing modifications for the devices examined in this study, future studies should assess other transducer models that may be compatible with PPE.

6. Conclusions

This study examined two bone conduction communication systems for use with full-face respirators. The systems were compared against the currently fielded technology, an air-conduction VPU. MRTs conducted in 66 dBA and 90 dBA background noise revealed enhanced speech intelligibility for the bone conduction systems over the current air-conduction system. In realistic 90 dBA noise, the bone conduction earpiece system yielded a 62% increase in speech intelligibility over the currently fielded system. This is a substantial improvement, and suggests that the latest bone conduction technology is a promising avenue for enhancing communication and improving safety and performance for civilian and military CBRNE personnel. The bone conduction systems tested would require minor modifications before fielding; most importantly, the earpiece system needs to include hearing protection which is compatible with PPE headgear.

7. References

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Appendix A. Volunteer Agreement Affidavit

This appendix appears in its original form, without editorial change.

STUDY PARTICIPANT CONSENT FORM
ARMY RESEARCH LABORATORY

Project Title: Enabling Speech Intelligibility in a Chemical Biological Radiological, Nuclear Operational Environment

Sponsor: U.S. Army Research Laboratory

Principal Investigator: Lamar Garrett, Maneuver & Mobility Branch, Aberdeen Proving Ground, MD, 410 417-2535, lamar.garrett.civ@mail.mil

Date: 31 July 2013

Why is this study being done?

This study will evaluate the intelligibility of speech transmitted through bone conduction with a tactical radio push-to-talk handset device that attaches to an M50 respirator to enable communication in a chemical, biological, radiological and nuclear operational environment.

What will happen if you join this study?

There are two operational scenarios used in the study: Pink Noise (66 dBA) and High Audible Noise (90 dBA). In both scenarios you will be seated in a stationary position in an open outdoor area. In both scenarios you will work together with one other participants wearing various communication systems listening to the speech signals transmitted through the systems. Your task will be to listen to speech test signals presented by a talker through communication systems and circle your answers on a paper form. The talker will be your colleague participating in the study. In some cases you will be asked to serve as a talker. You will conduct your task in a certain amount of a surrounding noise.

During the test you will be the talker or the listener. Each test will consist of 300 words (6 list of 50 words) presented by the talker in the carrier phrase "Number X. Circle the word ____, please." The number X will correspond to the number of the test item on the paper form. The test item on the form will be indicated be a block of 6 words which are your possible choices. You will need to select and circle the word that you heard. If you are unsure of what you heard, make your best guess.

After presentation of 300 words by a talker, the test will be interrupted for a few minutes (e.g., the talker and listener to switch) and another person becomes a talker. This procedure will be repeated five times, that is, until each of five people in your group will serve as a talker.

Such test sessions will last about 5 hours and will have ample time for breaks between individual tests. There will be eight test sessions conducted over the course two days.

What are the risks or discomforts of the study?

This study will evaluate the intelligibility of speech transmitted through a M50 respirator using an integrated bone conduction communication systems used in a Quiet or High Audible Noise conditions of operation.

Are there benefits to being in the study?

You will receive a free hearing test for participation in the research. No additional benefits other than satisfaction from participating in the study addressing well-being of the future U.S. Soldiers will be provided.

How will your privacy be protected?

The study staff will protect your data from disclosure to people not connected with the study. However, complete confidentiality cannot be guaranteed because officials of the U. S. Army Human Research Protections Office and the Army Research Laboratory's Institutional Review Board are permitted by law to inspect the records obtained in this study to insure compliance with laws and regulations covering experiments using human subjects.

Where can I get more information?

You have the right to obtain answers to any questions you might have about this study both while you take part in the study and after you leave the study site. Please contact the principal investigator listed at the top of the first page of this consent form for more information about this study. You may also contact the chairperson of the Army Research Laboratory, Institution Review Board, at (410) 278-5992 with questions, complaints, or concerns about this study, or if you feel this study has harmed you. The chairperson can also answer questions about your rights as a study participant. You may also call the chairperson's number if you cannot reach the study team or wish to talk to someone who is not a member of the study team.

WE WILL GIVE YOU A COPY OF THIS CONSENT FORM

____

Signature of Participant | Printed Name | Date

____

Signature of Person Obtaining Consent | Printed Name | Date

INTENTIONALLY LEFT BLANK.

Appendix B. MRT Answer Sheet for Listener

This appendix appears in its original form, without editorial change.

Start Time ___________

Device Type __________

Noise Level __________

Listener MRT Answer Sheet

Subject ID ___________

List Codeword ________

Today's Date __________

1	bat	bad	back	bass	ban	bath
2	bean	beach	beat	beam	bead	beak
3	bub	bus	but	buff	buck	bug
4	came	cape	cane	cake	cave	case
5	cut	cub	cuff	cup	cud	cuss
6	dig	dip	did	dim	dill	din
7	duck	dud	dung	dub	dug	dun
8	fill	fig	fin	fizz	fib	fit
9	hear	heath	heal	heave	heat	heap
10	kick	king	kid	kit	kin	kill
11	late	lake	lay	lace	lane	lame
12	map	mat	math	man	mass	mad
13	page	pane	pace	pay	pale	pave
14	pass	pat	pack	pad	path	pan
15	peace	peas	peak	peal	peat	peach
16	pill	pick	pip	pig	pin	pit
17	pun	puff	pup	puck	pus	pub
18	rave	rake	race	rate	raze	ray
19	sake	sale	save	sane	safe	same
20	sad	sass	sag	sack	sap	sat
21	seep	seen	seethe	seed	seem	seek
22	sing	sit	sin	sip	sick	sill
23	sud	sum	sub	sun	sup	sung
24	tab	tan	tam	tang	tack	tap
25	teach	tier	tease	teal	team	teak
26	led	shed	red	bed	fed	wed
27	sold	told	hold	fold	gold	cold
28	dig	wig	big	rig	pig	fig
29	kick	lick	sick	pick	wick	tick
30	book	took	shook	cook	hook	look
31	hark	dark	mark	lark	park	bark
32	gale	male	tale	bale	sale	pale
33	peel	reel	feel	heel	keel	eel
34	will	hill	kill	till	fill	bill
35	foil	coil	boil	oil	toil	soil
36	fame	same	came	name	tame	game
37	ten	pen	den	hen	then	men
38	pin	sin	tin	win	din	fin
39	sun	nun	gun	fun	bun	run
40	rang	fang	gang	bang	sang	hang
41	tent	bent	went	dent	rent	sent
42	sip	rip	tip	dip	hip	lip
43	top	hop	pop	cop	mop	shop
44	meat	feat	heat	seat	beat	neat
45	kit	bit	fit	sit	wit	hit
46	hot	got	not	pot	lot	tot
47	nest	vest	west	test	best	rest
48	bust	just	rust	must	gust	dust
49	raw	paw	law	jaw	thaw	saw
50	way	may	say	gay	day	pay

Appendix C. Example MRT Phrase List for Talker

This appendix appears in its original form, without editorial change.

Start Time ___________ **Alpha A** Subject ID ____________
Device Type _________ List Codeword Alpha A
Noise Level __________ Today's Date __________

Talker MRT Phrase List

1. Mark the bath again.
2. Mark the beam again.
3. Mark the bug again.
4. Mark the cape again.
5. Mark the cuff again.
6. Mark the dip again.
7. Mark the dub again.
8. Mark the fill again.
9. Mark the hear again.
10. Mark the kit again.
11. Mark the lake again.
12. Mark the map again.
13. Mark the page again.
14. Mark the pad again.
15. Mark the peace again.
16. Mark the pip again.
17. Mark the pup again.
18. Mark the race again.
19. Mark the save again.
20. Mark the sag again.
21. Mark the seen again.
22. Mark the sip again.
23. Mark the sung again.
24. Mark the tap again.
25. Mark the tease again.
26. Mark the red again.
27. Mark the fold again.
28. Mark the rig again.
29. Mark the pick again.
30. Mark the cook again.
31. Mark the hark again.
32. Mark the pale again.
33. Mark the heel again.
34. Mark the till again.
35. Mark the soil again.
36. Mark the fame again.
37. Mark the hen again.
38. Mark the pin again.
39. Mark the nun again.
40. Mark the sang again.
41. Mark the sent again.
42. Mark the dip again.
43. Mark the top again.
44. Mark the seat again.
45. Mark the hit again.
46. Mark the lot again.
47. Mark the nest again.
48. Mark the must again.
49. Mark the raw again.
50. Mark the may again.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
ANOVA	analysis of variance
ANSI	American National Standards Institute
ASA(ALT)	Assistant Secretary of the Army for Acquisition, Logistics, and Technology
ARL	U.S. Army Research Laboratory
CAE	Combat Arms Earplugs
CANE	Combined Arms in a Nuclear/Chemical Environment
CBRNE	Chemical, Biological, Radiological, Nuclear, and Explosive
CVC	consonant-vowel-consonant
dBA	decibels (A-weighted)
EAR	Environment for Auditory Research
FoS	Family of Systems
FDTE	Force Development Test and Experimentation
HaMMER	Hazard Mitigation, Materiel and Equipment Restoration
HL	hearing level
HRED	Human Research and Engineering Directorate
HPD	hearing protection device
JSGPM	Joint Service General Purpose Mask
JSLIST	Joint Service Lightweight Integrated Suit Technology
KASTLE	Kiple Acquisition Science Technology Logistics Engineering
MBITR	Multiband Inter/Intra Team Radio
MRT	Modified Rhyme Test
PPE	personal protective equipment
PTT	push-to-talk

RAU	rationalized arcsine unit
VAA	volunteer agreement affidavit
VPU	Voice Projection Unit

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